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TECHNICAL NOTE

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SOURCES OF ERRORS IN LOCATING WEATHER SYSTEMS IN IMAGERY FROM POLAR-ORBITING SATELLITES-- A SHORT PRIMER IN SPACECRAFT GEOMETRY

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Accurate tracking of meteorological systems in satellite imagery requires recognition and correction of location errors. This technical note discusses three sources of location errors: satellite attitude, orbital anomalies, and satellite perspective. These errors may be corrected in the gridding process.

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INTRODUCTION

Imagery from meteorological satellites has assumed an every-increasing role in support to the DoD's Pacific Typhoon Warning Service and other operations Pacific-wide. When a meteorological system is tracked via satellite images, in order to provide proper input to the customer, the analyst must determine whether spacecraft geometry or system errors have influenced the presentation of the system (e.g., typhoon) in the image. He/she then must correct these errors when possible and include an accurate position (usually with reference to a latitude/longitude grid) in the information supplied to the customer.

This paper discusses the elements of spacecraft geometry and how attendant errors may be recognized and corrected. It will be valuable to the DMSP analyst when used with its companion paper 1WW FM 81-004 on gridding techniques. This note may also serve to introduce supported operations personnel to some of the problems the staff weatherman routinely solves.

SOURCES OF LOCATION ERRORS. There are many sources of location errors that a meteorological satellite analyst could encounter. At least two of these will not be discussed here. These two - equipment alignment problems and erroneous tracking (ephemeris) data are, respectively: beyond the scope of this text, and too erratic in nature to be handled except on a case-to-case basis. The discussion will center on these error sources: spacecraft attitude, orbital anomalies, and spacecraft perspective.

Spacecraft Attitude. For polar orbiting spacecraft, accurate data location is based on two assumptions. First, when the sensor is viewing straight

down, it is assumed to be looking directly at the satellite subpoint -(where the subpoint is defined as the projection of the spacecraft through the vertical to a point on the surface of the earth). Second, accurate data location assumes that the sensor scans in a path over the earth that is perpendicular to the satellite subtrack. (The satellite subtrack is defined as the line traced on the surface of the earth by the subpoint as the spacecraft completes its orbit.) In reality, small deviations occur due to changes in the spacecraft attitude. These deviations can be expressed in terms of rotations about the three axes which define the satellite's frame of reference. These rotations are called: roll, pitch and yaw, and are illustrated in Figure (1).

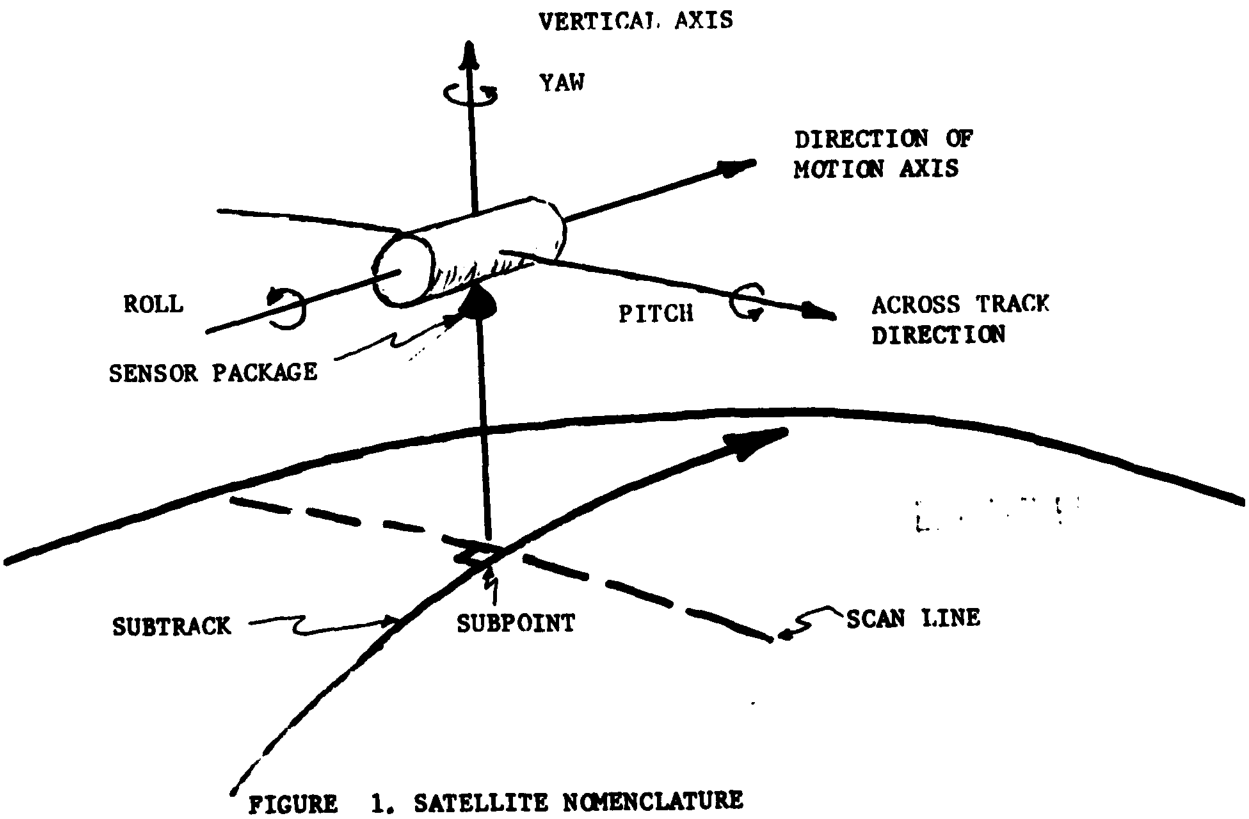

FIGURE 1. SATELLITE NOMENCLATURE

Roll is the rotation of the spacecraft about the direction of motion axis. A roll error will shift the center of the field of view of the sensor package to the right or left of the satellite subpoint. As a result, the data center line will be similarly shifted to the right or left of the subtrack. Primarily, roll errors affect the longitudinal accuracy of a position fix. Since all recent generation DMSP and NOAA spacecraft are capable of maintaining a zero roll error, roll error calculations and corrections are seldom, if ever, required.

Pitch is the rotation of the spacecraft about its longitudinal axis. This axis lies in the local horizontal plane of the spacecraft and perpendicular to the direction of motion axis. A pitch error causes the spacecraft to nose up (positive pitch) or down (negative pitch) as the spacecraft orbits the earth. As a result, the sensor package scans ahead of or behind the satellite subpoint, respectively. Thus, a pitch error causes data scan lines to be displaced along, yet still perpendicular to, the subtrack. Pitch errors primarily affect the latitudinal accuracy of a fix. Significantly, several other types of "along track" errors manifest themselves as apparent pitch errors. These errors include: yaw errors, errors in the nodal crossing times (bad tracking data); errors due to the elliptical shape of the orbit; and operator errors in synchronizing the orbital time clock. Fortunately, these errors are all easily corrected if the proper geographic gridding techniques are employed. These techniques are described in 1WW FM 81/004, Gridding Images from Polar Orbiting Meteorological Satellites.

Yaw is the rotation of the spacecraft about its vertical axis. A yaw error means that the spacecraft is turned slightly sideways (as an aircraft in a crosswind) to its direction of motion. As a result, a yaw error slightly rotates the scan lines so that they are no longer perpendicular to

the satellite subtrack. Therefore, a yaw error manifests itself as a pitch error that is positive on one side of the subtrack, negative on the other side of the subtrack, zero at the subpoint, and increases linearly as the sensor scans away from the subpoint and towards the edge of scan. Yaw errors are relatively common, but also can be corrected by using geographic gridding techniques. However, it is very important to remember that the magnitude of the yaw error varies across the track. Therefore, care must be taken to use a geographical feature with the same across track alignment as the center of the cloud to be fixed. This will insure that the sign and magnitude of the yaw error correction correspond to the actual amount of adjustment needed.

Orbital Anomalies. The current generation of NOAA and DMSP spacecraft are placed in a sun-synchronous, 450 nautical mile altitude orbit. Although an attempt is made to acquire a perfectly circular orbit (zero eccentricity) with a precise inclination angle (98.747 degrees), actual orbits are known to differ slightly from the design ideal. Unfortunately, the standard grids used in data location were designed based on the ideal orbital configuration. Therefore, slight deviations in either eccentricity or inclination will result in data location errors. From orbital mechanics we know that every orbit is elliptical. Eccentricity is a measure of the circularity of an ellipse. The more egg-shaped the orbit, the larger the eccentricity. Interestingly, the longer a spacecraft is in orbit, the more circular the orbit becomes and thus the smaller the value of its eccentricity. DMSP and NOAA spacecraft have orbital eccentricities that range from 0.0009 to 0.002, approximately. These are very circular orbits. To illustrate, assuming an eccentricity of 0.001 for a 450 nautical mile orbit (semi-major axis of

3,890 nm), the difference in the lengths of the semi-major and semi-minor axes is less than 11 feet.

How can such a nearly circular orbit contribute to significant data location errors? The answer is really quite simple. Figure (2) shows an ellipse with its basic components illustrated as follows: eccentricity (e), semi-major axis (a), semi-minor axis (b), center of ellipse (0), and foci (f). Again, from orbital mechanics we know that the center of the earth is not located at 0, but at one of the two foci (f), instead. Further, the foci are at a distance (ae) from the center of the ellipse (0). It is this distance, ae, that causes the observed altitude variation of the orbit. In

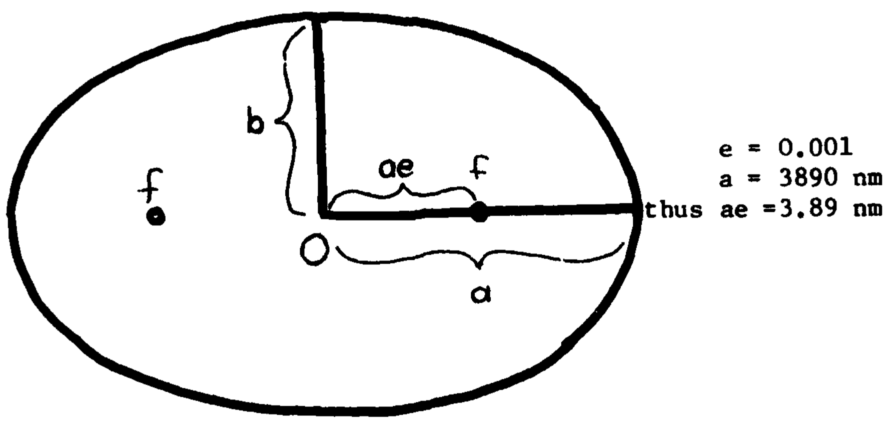

FIGURE 2. EARTH ORBITAL ELLIPSE

fact, the actual altitude variation is 2ae or 7.78 nm for a 450 nm orbit and eccentricity of 0.001. Therefore, even the very circular orbit of the DMSP results in significant altitude variations and it is these changes in altitude that, uncorrected, result in data location errors.

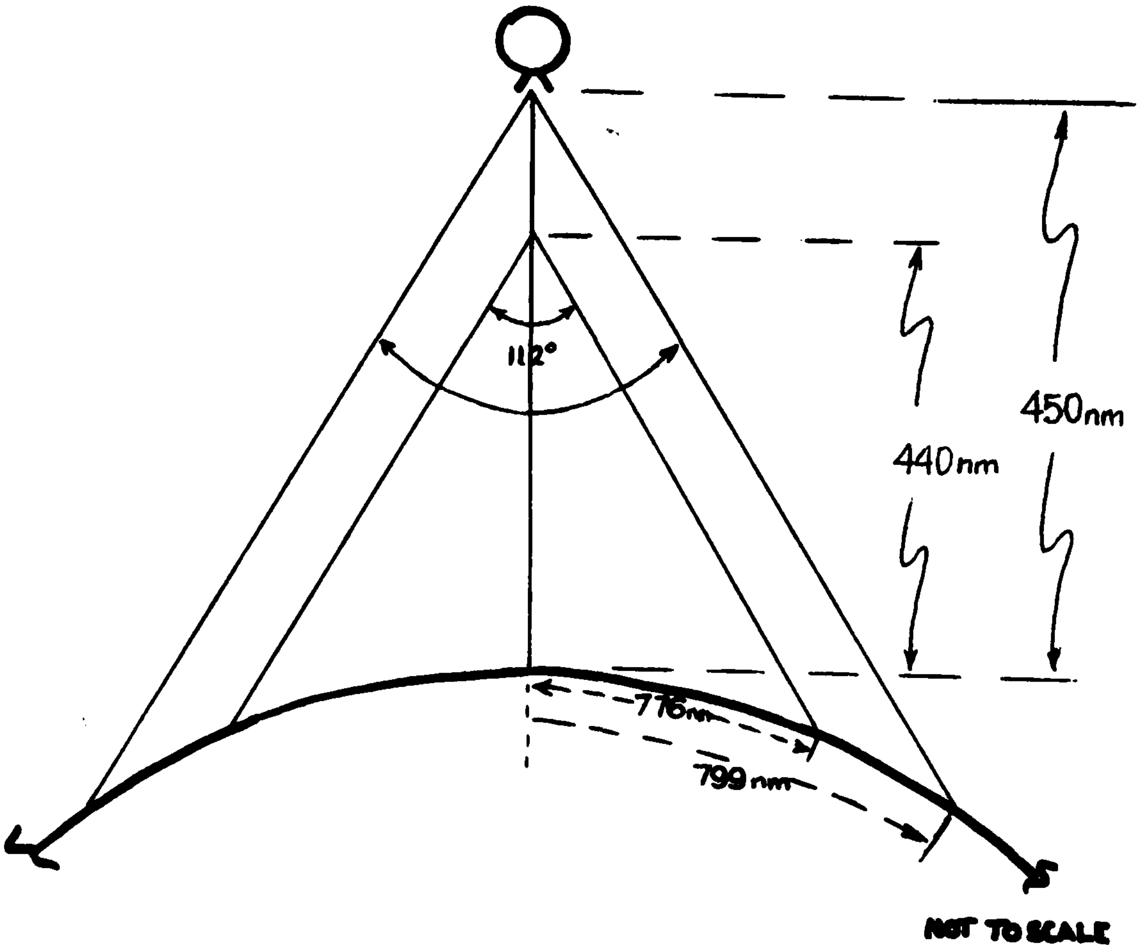

FIGURE 3. ALTITUDE EFFECTS

Figure (3) shows how a 10 nm variation in altitude affects the imagery. With a fixed field of view (112° for DMSP), the lower the spacecraft orbits, the smaller the scan of the earth's surface and vice versa. Therefore, as the spacecraft orbits the earth, the data scan is alternately compressed and stretched as the altitude of the spacecraft decreases or increases, respectively. Further, from Kepler's law of equal areas, the spacecraft travels faster at the low point in the orbit than at higher altitudes. Thus, there will also be an along track compression and stretching of the data induced

by the elliptical shape of the spacecraft's orbit.

Fortunately, the DMSP electronics equipment can compensate for both along and across track distortions. The Altitude Error Correction Unit normalizes data taken from various altitudes by adjusting both the scan width and the film speed during exposure. The result is a normalized image identical in scale to imagery obtained from a spacecraft flying a nominal 450 nm orbit and, therefore, to the standard DMSP grid. Note that this correction will only be accurate for the spacecraft altitude entered into the machine. Since the spacecraft constantly changes its altitude, location errors can be expected at other points along the pass. While small, these errors can be made even smaller by selecting an altitude setting corresponding to the actual altitude of the spacecraft as it passes over the cloud area or tropical cyclone of interest. For DMSP, such altitudes can be determined by consulting the daily Data Memory message for the spacecraft to determine the argument of perigee. Once the argument of perigee is determined, the altitude setting for the latitude of interest is obtained by consulting the Universal Tracking and Subpoint Listing. Similar altitudes for NOAA spacecraft are contained in the daily APT Predit messages (TBUS bulletins).

Another error induced by the elliptical orbit of the spacecraft resembles a pitch error. As previously mentioned, the spacecraft moves at different speeds along its elliptical path, slower at high altitudes and faster at low altitudes. The resulting accelerations and the fact that the earth is not the exact center of the orbit means that the spacecraft is not always looking "straight down" relative to the surface of the earth. This type of pitch error can easily be corrected using geographical gridding techniques.

A final data location error caused by an orbital anomaly involves the orbital inclination angle. The inclination angle is the angle between the satellite's orbital plane and the earth's equatorial plane. By convention, the angle is measured as the satellite crosses the equator northbound (ascending node) from the equatorial plane counter-clockwise to the orbital plane as shown in Figure (4).

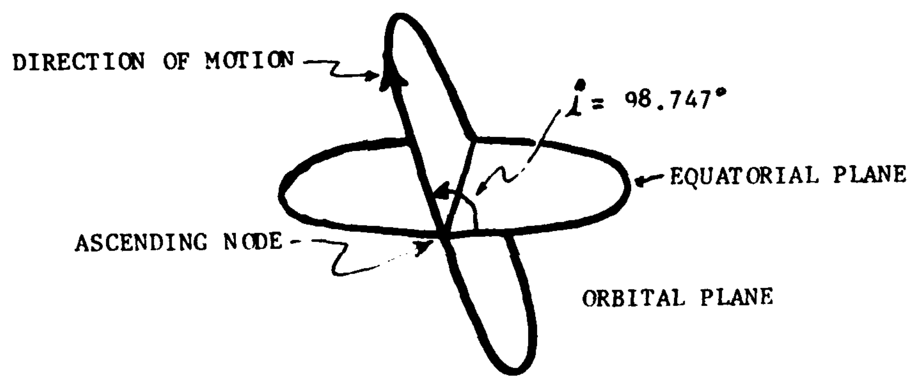

FIGURE 4. INCLINATION ANGLE

The nominal inclination angle of a DMSP spacecraft (the value assumed in grid construction) is 98.747 degrees. Actual values of inclination angle (and other orbital parameters, as well) are transmitted periodically as Special Message data (code 5) added to the spacecraft's daily data message. A deviation of the inclination angle from its nominal value will mostly affect the longitudinal accuracy of a fix. Fortunately, these deviations are usually insignificant and can be compensated for by using geographic gridding techniques.

SPACECRAFT PERSPECTIVE. The final error source concerns spacecraft perspective. The imagery produced by the DMSP electronics rack is rectified so that the earth scene appears as a flat surface. One must remember that this rectification is an artificial enhancement of the data and that curvature effects are still present. Further, since curvature effects are greater near the horizon, the perspective problem is greatest at the edges of the data.

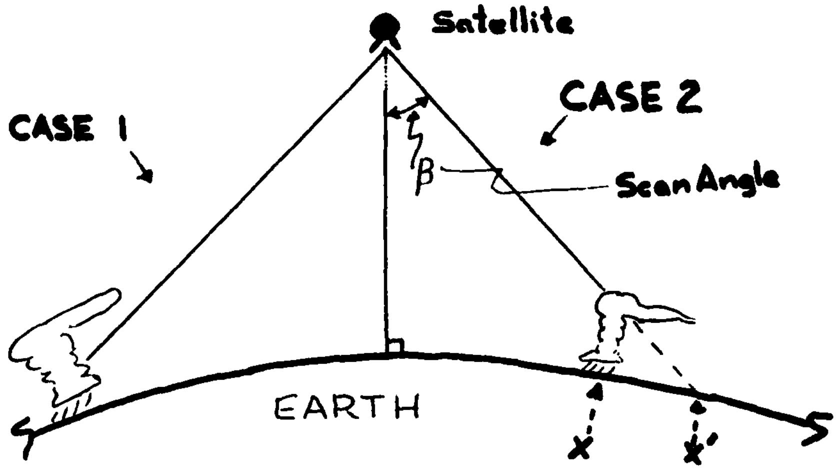

FIGURE 5. PERSPECTIVE PROBLEMS

Figure (5) illustrates the two most common edge-of-scan perspective problems. First, the rectified image makes it appear that clouds near the edge of the data are being viewed from directly overhead. In fact, as shown in case 1, clouds at the extreme edge of scan are being viewed from the sides. This will affect not only the appearance of the cloud, but the observed temperature as well, since the sides of the cloud will radiate at a warmer temperature than the actual cloud top which is higher and colder. In case 2, the second problem is illustrated. Here a cloud which is actually

at point X will appear to be at point X'. The case 2 situation is easily corrected by applying a factor known as the beta angle correction which always moves the cloud closer to the satellite subpoint.

SUMMARY

A sound knowledge of satellite geometry will enable analysts to provide customers with accurate locations of meteorological phenomena. Errors produced by spacecraft attitude, orbital anomalies, and spacecraft perspective are usually easily corrected in the gridding process.

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